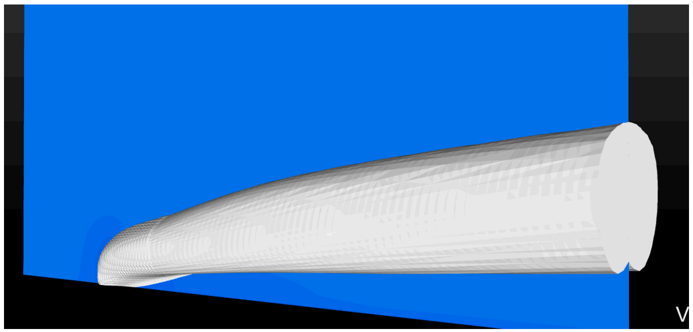

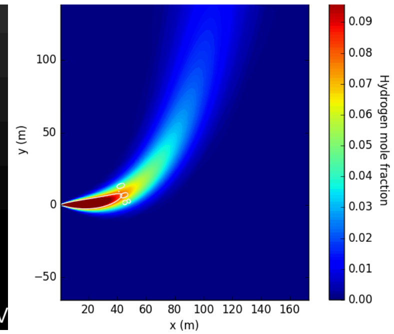

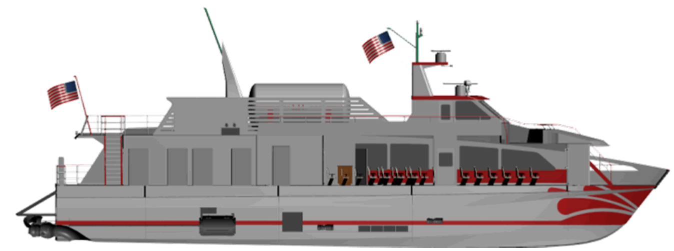

Hydrogen Fueled Ferry Feasibility Study and CFD Modeling of Leak Scenarios

Gabriela Bran-Anleu

Myra Blaylock, Joe Pratt

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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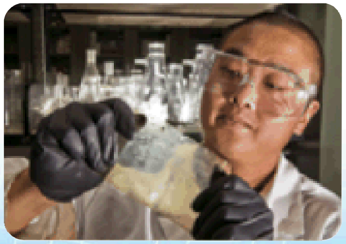
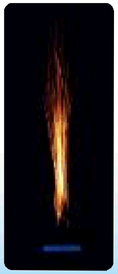
Sandia National Laboratories
"Exceptional service in the national interest"

- Largest National Lab in U.S.
  - U.S. Department of Energy (DOE)
  - ~12,000 employees
  - ~US$2.3B/yr from DOE, other federal agencies, and private industry
  - H2 Program in Livermore, CA (HQ in Albuquerque, NM)
- Hydrogen program: 60+ years technical depth in a wide range of areas, which we apply to enable impactful clean energy solutions





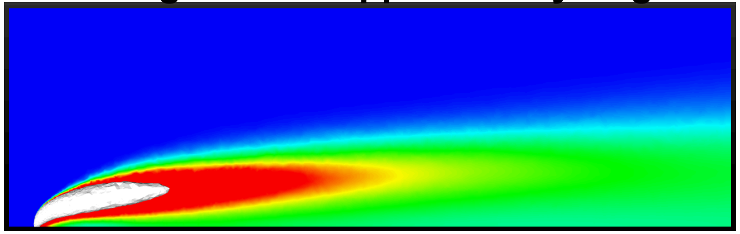

Sandia's *Zero Emission Maritime* Program

Maritime Hydrogen Fuel Cell Project (MarFC)

San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

Zero Emissions Research Oceanographic Vessel (ZERO/V)

IMO code development
Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



And more…

Visit: maritime.sandia.gov

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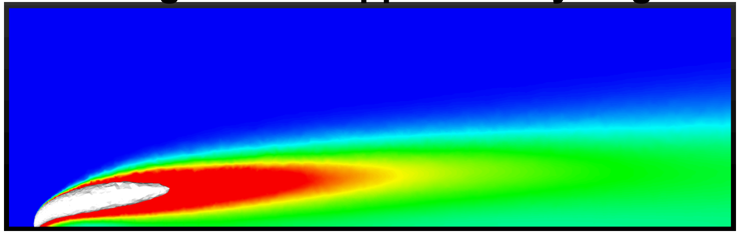

And more…

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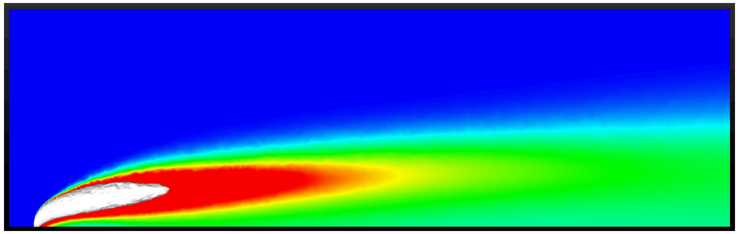
Outline

- SF-BREEZE Feasibility Study
  - Why H2
  - Initial design

San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

- Gas Dispersion Analysis
  1. Abnormal Blowdown from LH_2 Tank
  2. Normal "Boiloff"
  3. Leak in Fuel Cell Room

Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



Outline

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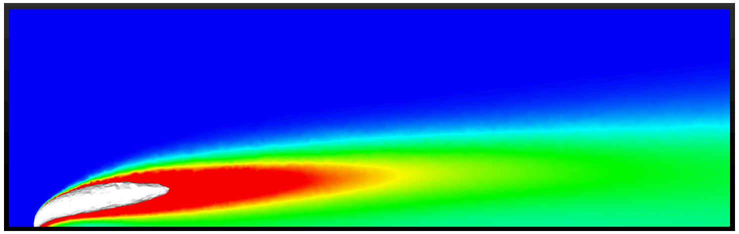
San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



SF-BREEZE Project Concept

High-speed H_2 Ferry

Engineering model of the SF-BREEZE

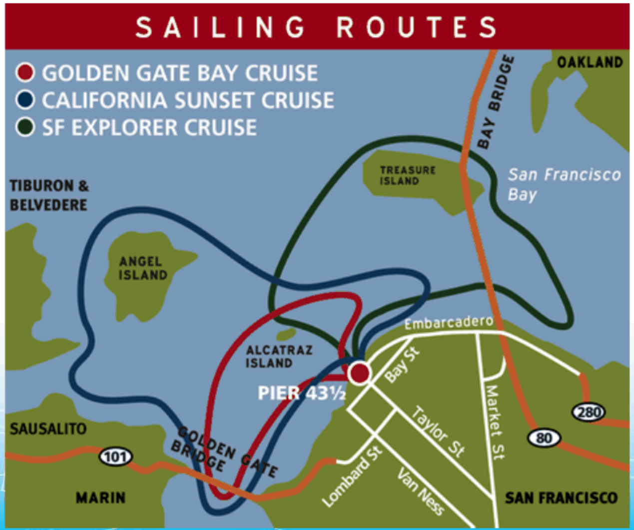
Dockside Fueling Station

Example existing dockside hydrogen station in Hamburg, Germany

Technically Possible? ***Accepted by Regulators?*** ***Commercially Viable?***

Red and White Fleet

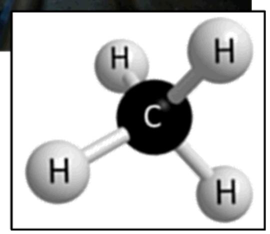
- Founded in 1892
- Offers over 5,000 sightseeing trips/yr under the Golden Gate Bridge.
- Fleet: 4 passenger vessels, steel mono hulls, 350 to 600 pax.
- Run 6 Tier III engines and 10 Tier II engines across their fleet to provide a service with the highest level of environmental responsibility
- In 2014, Mr. Escher made a commitment to providing their services on a **zero emission vessel**



Hydrogen is a combustible fuel, very similar to natural gas, but does not contain *carbon.*

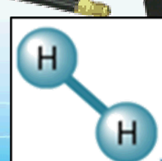
H_2O
CO
CO_2

Natural gas

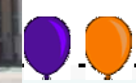


H_2O

Hydrogen



Hydrogen is the lightest gas

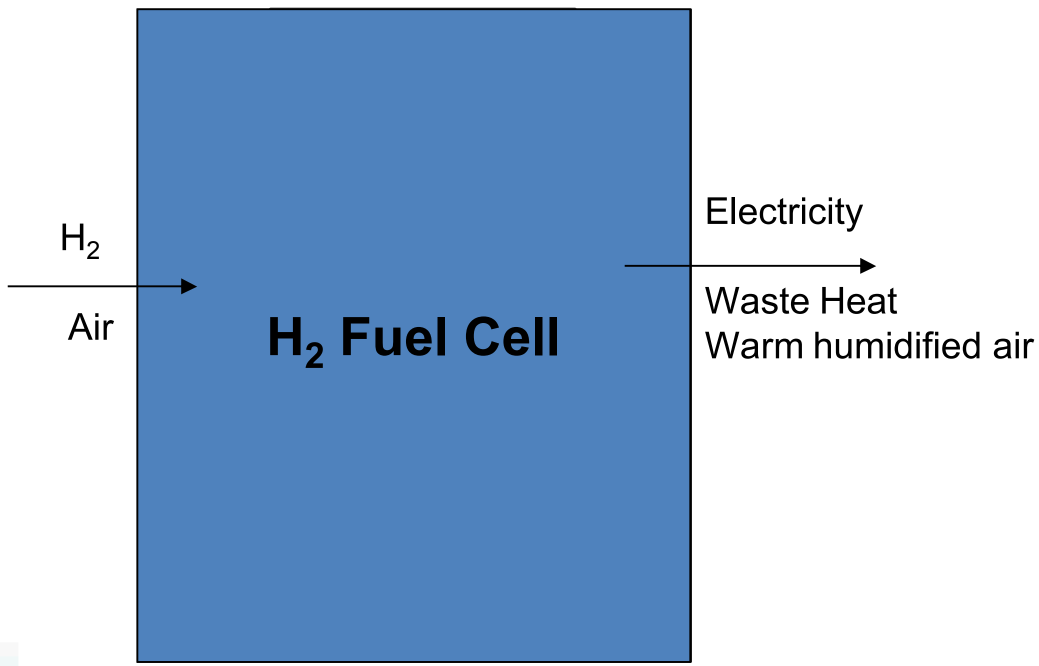


NG H_2

When hydrogen is used in a *Fuel Cell,* it produces ZERO pollution or greenhouse gas

Hydrogen Fuel Cell

$$2\ H_2 + O_2 \rightarrow 2\ H_2O$$



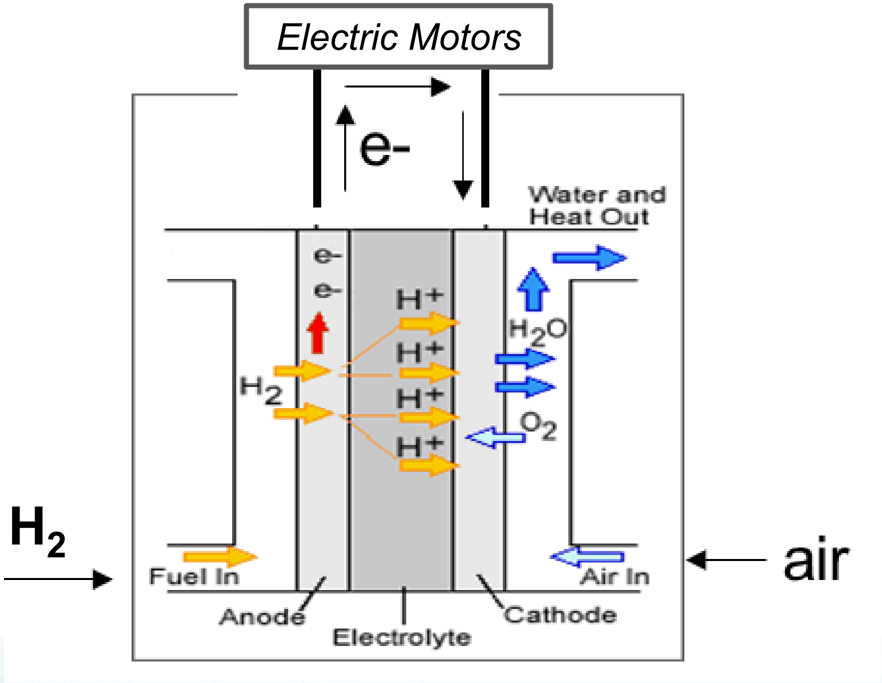
Hydrogen Fuel Cell Room

Photos Courtesy Ryan Sookoo, Hydrogenics

When hydrogen is used in a *Fuel Cell,* it produces ZERO pollution or greenhouse gas

Hydrogen Fuel Cell

$2\ H_2 + O_2 \rightarrow 2\ H_2O$



Hydrogen Fuel Cell Room

Photos Courtesy Ryan Sookoo, Hydrogenics

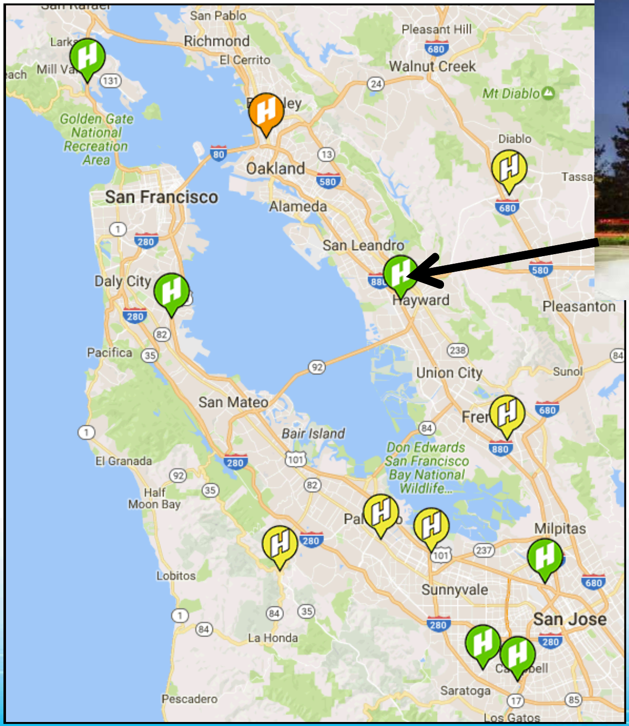
Hydrogen fueling stations and fuel cell electric vehicles are in the Bay Area today

Hyundai Tucson

Toyota Mirai

Honda Clarity

AC Transit buses



Hayward hydrogen fueling station

Ways to Store Hydrogen on the SF-BREEZE

Gaseous tanks

~2,000 psi steel or aluminum

5,000-10,000 psi carbon fiber composite assemblies

Liquid hydrogen

Metal Hydride

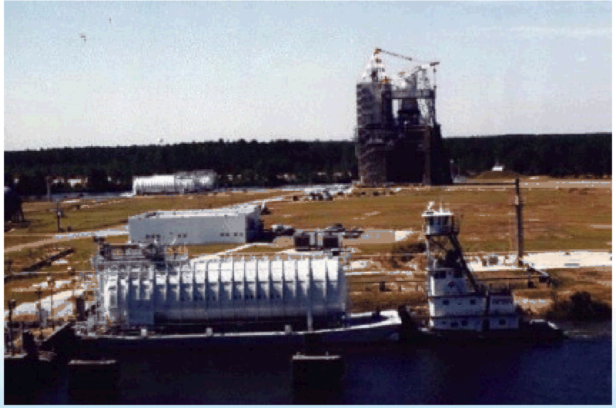
Liquid hydrogen is the lightest option for the SF-BREEZE

LH_2 has been safely used for decades

AC Transit bus fueling facility, Emeryville

- LH_2 tanks are double walled vacuum insulated stainless steel tanks with steel shell.

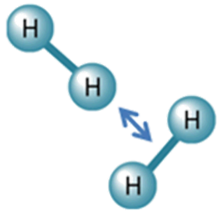
- A typical trailer can deliver 4000 kg (~15,000 gallons) at a time.



Vessel design with LH_2 is similar to that with LNG

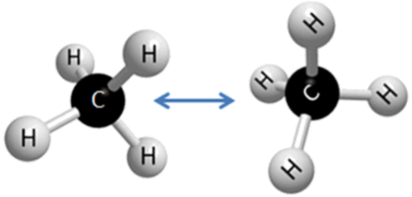
Commonalities

- Similar combustion properties
- Same safety design method:
  - Leak avoidance and monitoring
  - Minimize ignition sources
  - Provide ventilation



Major Differences

- H_2 is much more buoyant than CH_4 - even when very cold
- LH_2 is colder and can condense/freeze air



For the same amount of stored energy:

- **LH_2 is lighter** (m = 0.38 x LNG)
- **LH_2 is bigger** (V = 2.4 x LNG)

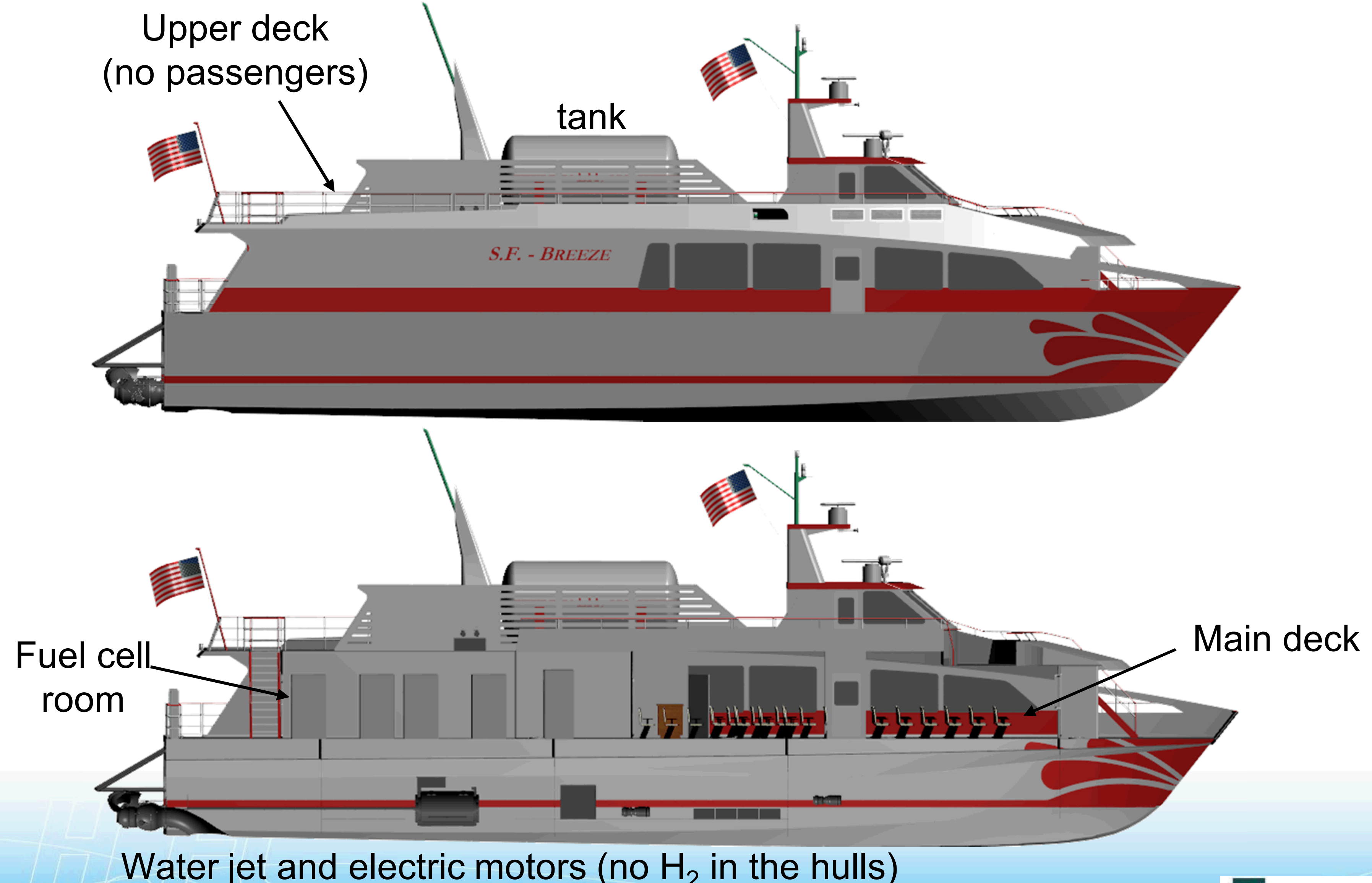
The current use of LNG as a maritime propulsion fuel is paving the way for use of LH_2 for vessels.

SF-BREEZE Operating Requirements

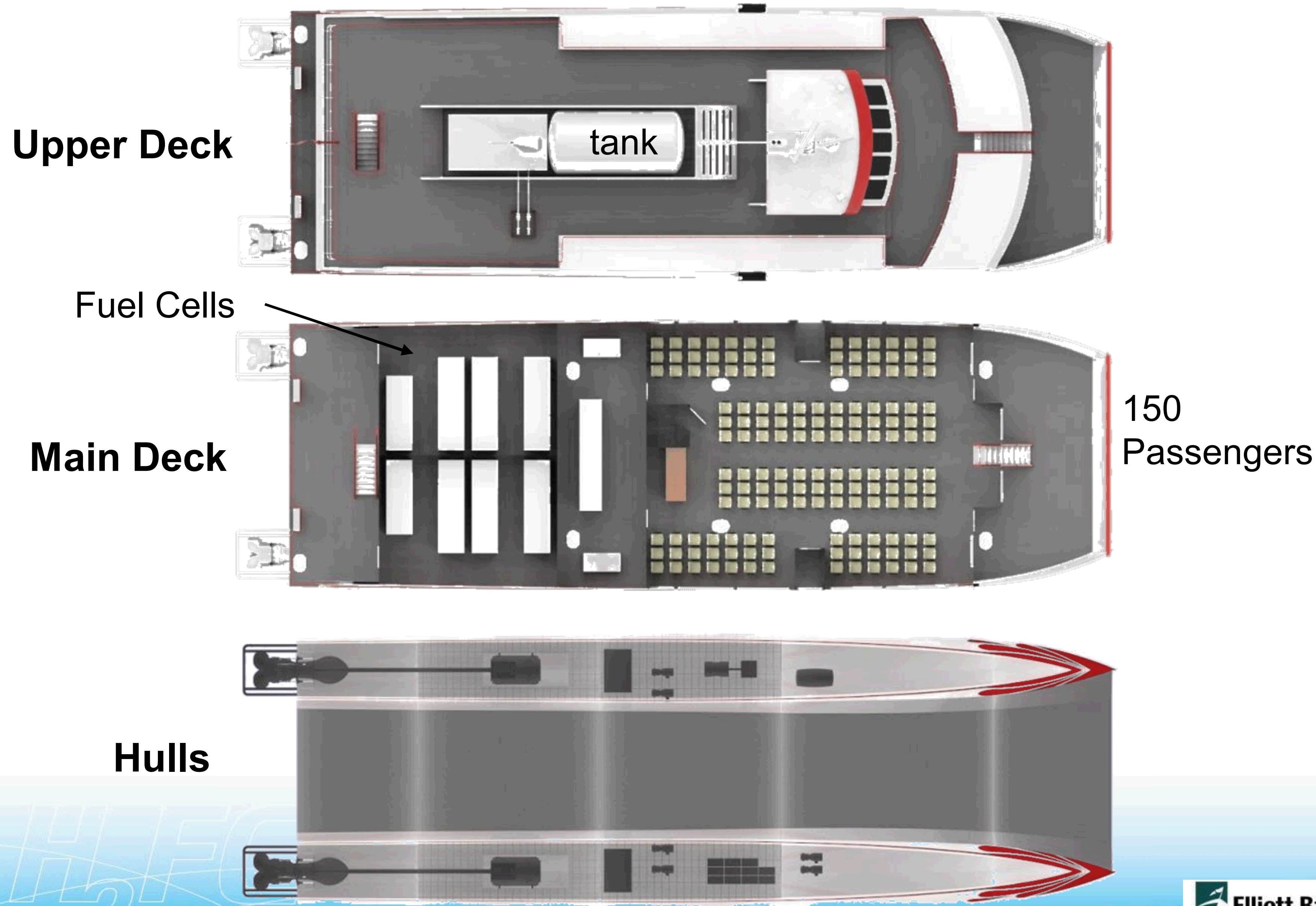
- High-speed commuter ferry in an ocean bay environment – true commercial competitive service
- **35 kts** top speed, **23 nm** one-way
- Each round trip would use about 400 kg LH_2
- Daily logistics:
  1. Two morning round trips (~100 nm)
  2. Refuel in less than 1 hr at midday
  3. Two afternoon round trips (~100 nm)
  4. Refuel again at night

The final SF-BREEZE design meets all requirements

Naval Architecture by Elliott Bay Design Group



Elliott Bay Design Group

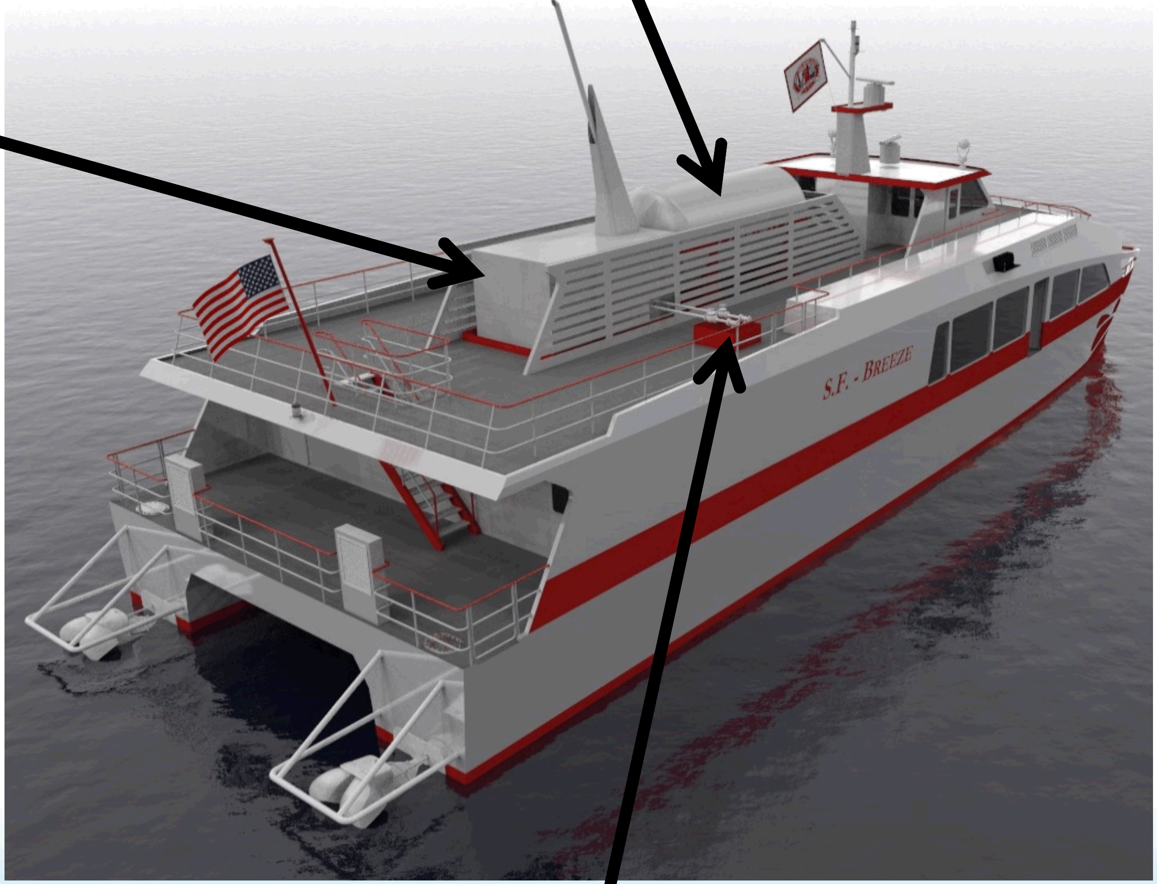


Elliott Bay Design Group

SF-BREEZE Fueling Characteristics

1,200 kg (~4,800 gallons) LH_2 tank

Vaporizers



Bunkering connection

Each round trip uses about **400 kg** of LH_2

A comprehensive regulatory assessment was performed by all partners.

USCG:

- Office of Design and Engineering Standards
- Marine Safety Center
- Sector San Francisco
- Liquid Gas Carrier National Center of Expertise

American Bureau of Shipping

Elliott Bay Design Group

Sandia National Labs

MARAD

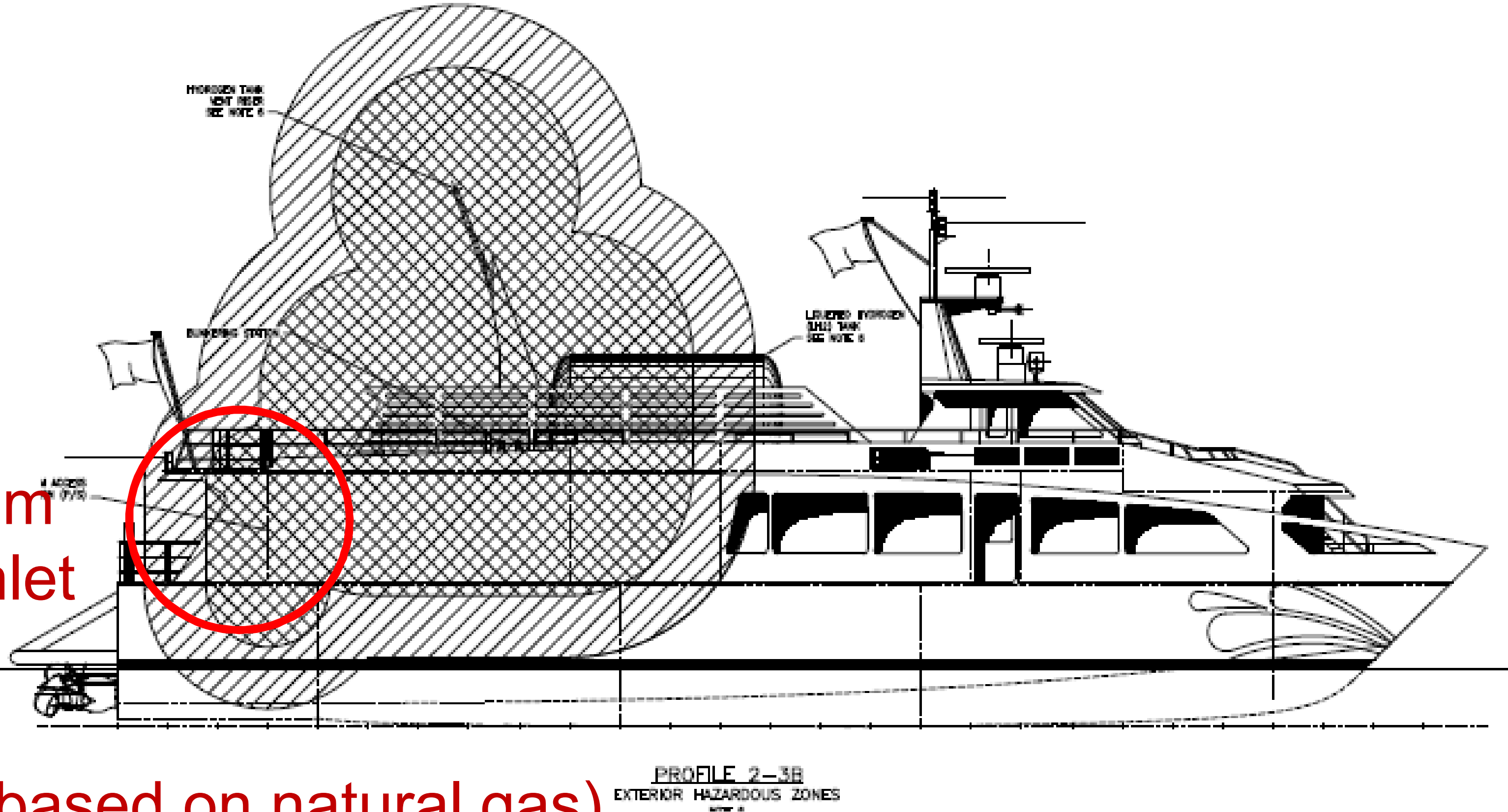
Red and White Fleet

Findings:

- No regulatory show-stoppers
- 62 of 68 design aspects found covered by design basis documents
- *Gas dispersion analyses required for suggested hazardous zone exceptions*

Example hazardous zone exception

Hydrogen



Fuel cell room ventilation inlet location in conflict with IGF 13.3.5 (based on natural gas)

- Qualitatively, it appears that the high buoyancy of hydrogen precludes the need for a hazardous zone to extend lower than the elevation of release.
- Quantitative gas dispersion analysis is required for Class and Flag approval.

Outline

- SF-BREEZE Feasibility Study
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  - Initial design

San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

- **Gas Dispersion Analysis**
  1. Abnormal Blowdown from LH_2 Tank
  2. Normal "Boiloff"
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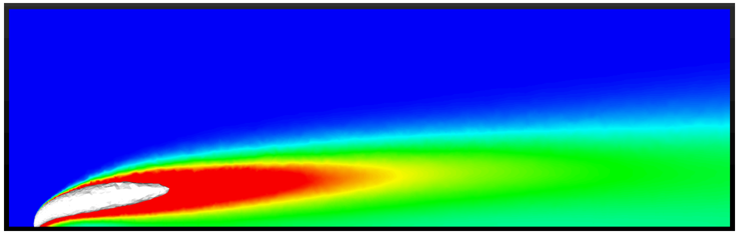
Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen

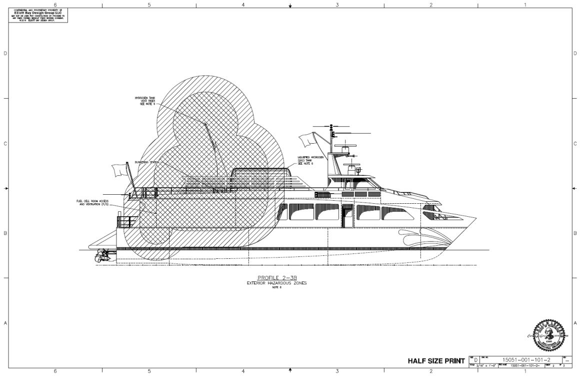


Gas Dispersion Analysis

- Goal
  - Inform accurate overall hazardous zone requirements for hydrogen
- Benefit of defining hazardous zones for hydrogen
  - Enable faster and easier approval by reducing the need for gas dispersion studies on every future vessel submitted for approval
  - Avoid placing undue burden on vessel design and layout
  - Avoid situations that are unsafe
- Approach
  - Define most significant leak scenarios with stakeholders: US Coast Guard, American Bureau of Shipping, DNV-GL
  - Perform detailed modeling of these initial scenarios
  - Define whether a need for follow-on scenario studies

H_2 Release Scenarios

1. Abnormal Blowdown from LH_2 Tank
   - Are the Hazardous Zones in the right place?
   - Maximum release
   - Docked vs. moving



2. Normal “Boiloff”

3. Leak in Fuel Cell Room
   - Equivalent to engine room
   - Concerned about ventilation, overpressure and fire.
   - Sensors will shut off supply quickly

©Hydrogenics Corp.

Computational Fluid Dynamics (CFD)

- Sandia's Sierra Suite: Fuego – incompressible flow solver
  - Reynolds' Averaged Navier-Stokes (RANS)
  - Variables adapted for "jet in crossflow" conditions
  - Small scale turbulence is averaged, so dissipation is under predicted
- Wind speeds:
  - 0 knots – calm day at docks
  - 5 knots – normal wind at docks
  - 30 knots – moving or very windy at docks
- Wind is assumed constant laminar flow for entire length of the release
  - Conservative results, especially for long-length releases and high-wind speeds

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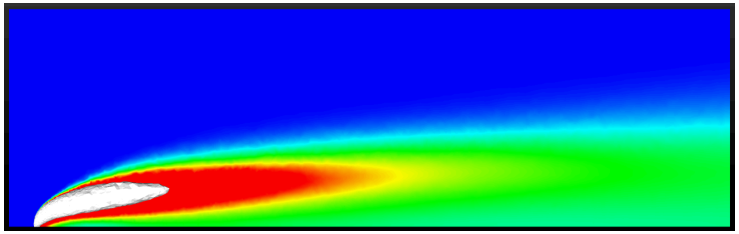
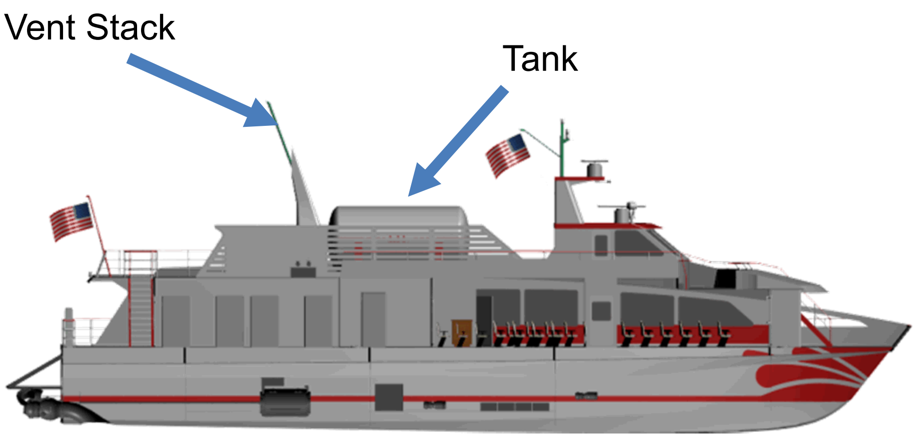


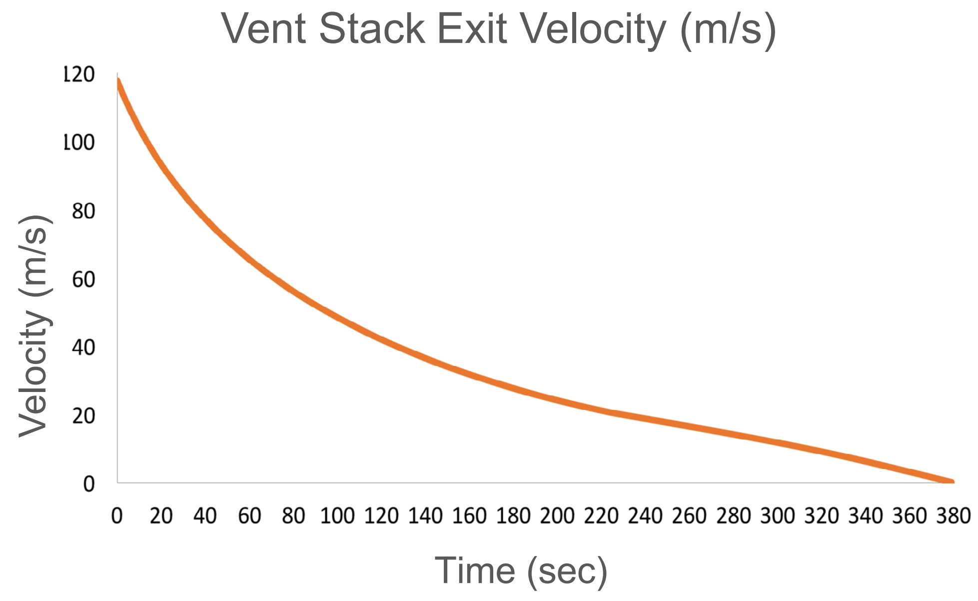
Scenario 1: Abnormal Blowdown
Opened Pressure Relief Device from Large LH_2 Tank

- Full Blowdown of LH_2 tank through a Vent Stack
  - Tank Dimensions
    - 150 PSI
    - ~4500 gallons
    - 1 inch leak through valve
    - ~ 6 minutes to empty
  - Vent Stack
    - ~7 inch internal diameter
    - 25 feet tall (7.5 m)
    - Modeled as straight up

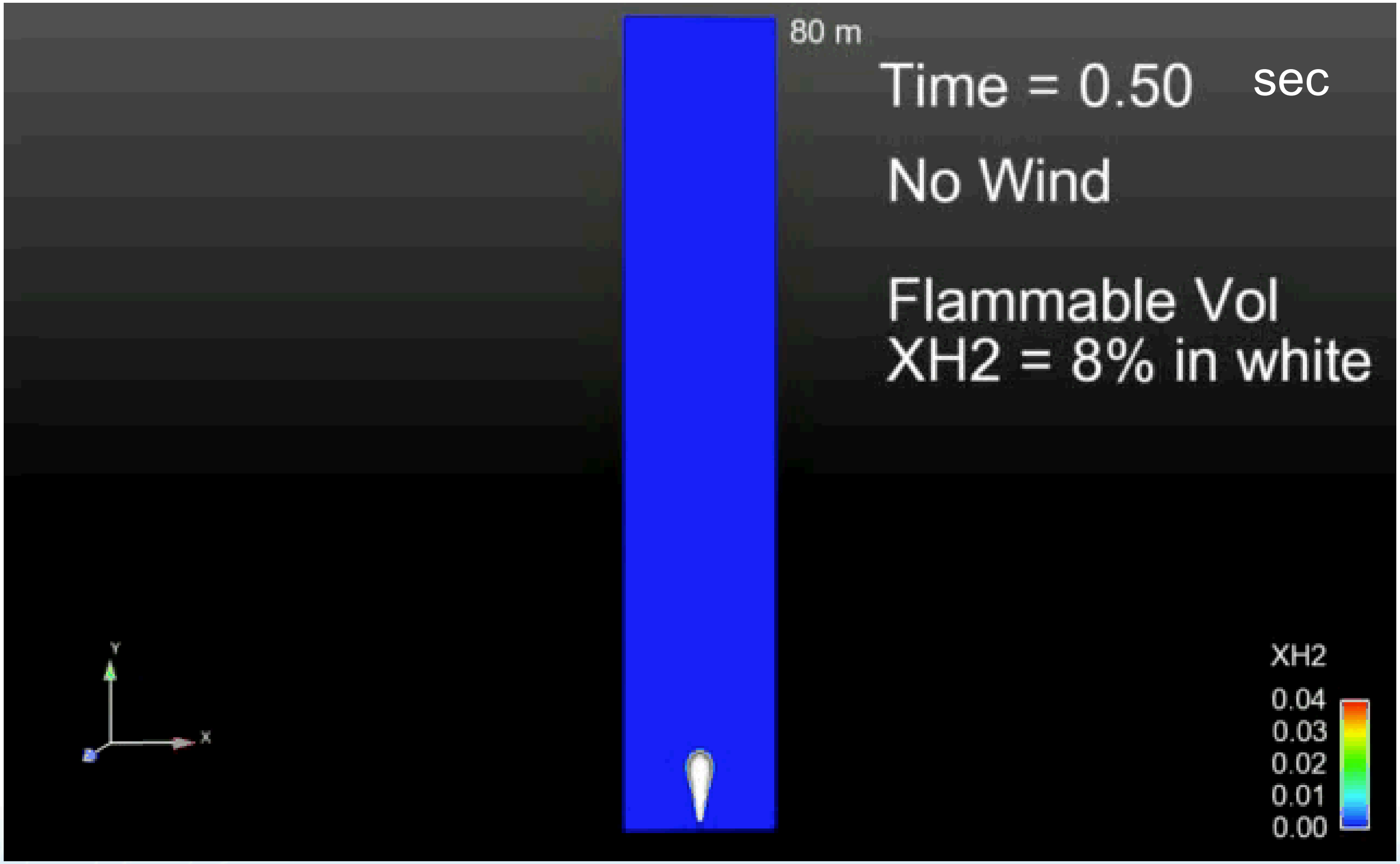


Worst Case: Blowdown when tank is 90% vapor

- Two phases in tank: liquid and vapor
- Leak will dump vapor quickly, then be limited to “boil off” amounts
  - Only modelled the vapor release
- Biggest H_2 release comes from tank with mostly vapor
  - 10% liquid for cases shown
- Tank empties vapor in ~6 minutes

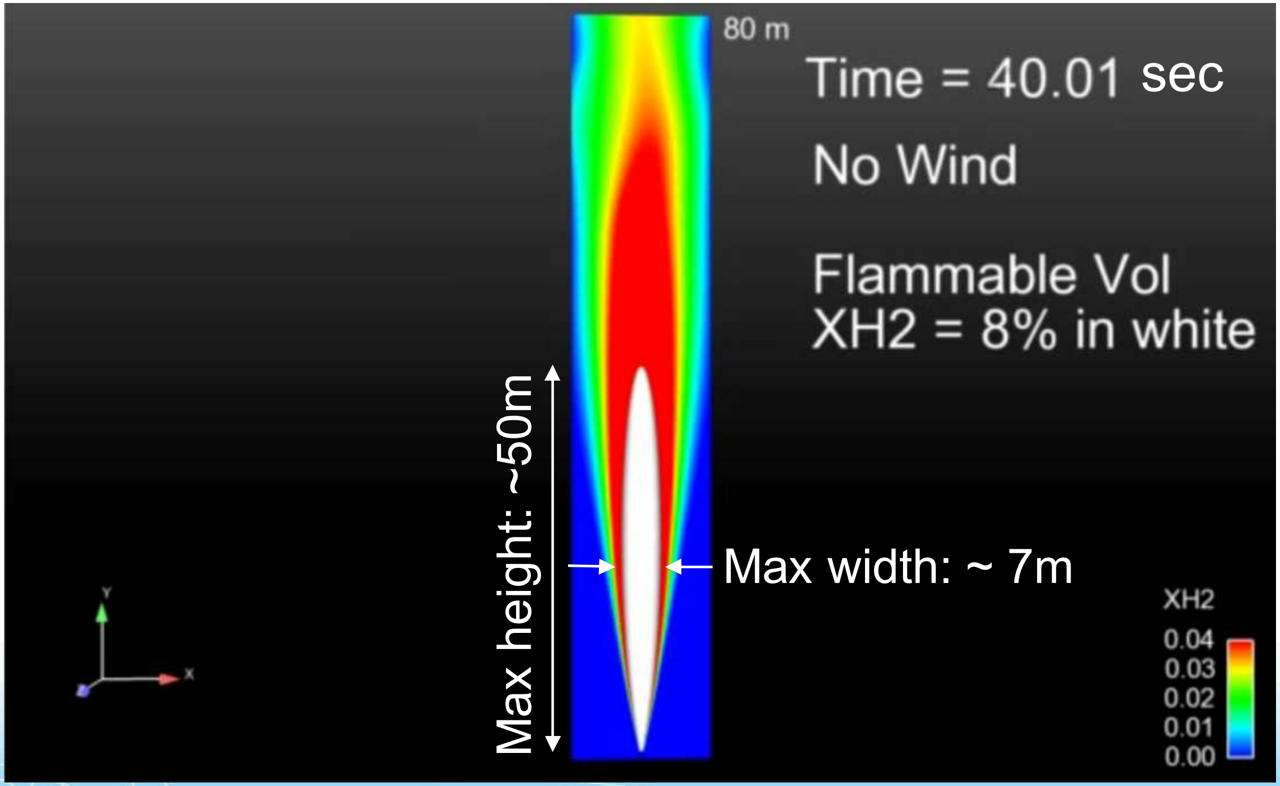


CFD of SF-BREEZE H_2 Release Without Wind



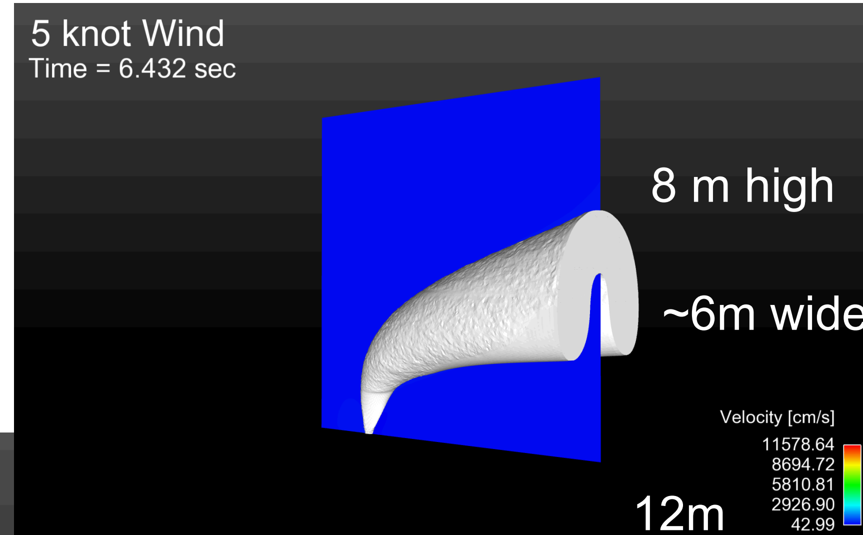
CFD of SF-BREEZE LH_2 Release Without Wind

- White shows flammable mass with volumetric concentration between 8%-75%
- Flammable Region Reaches ~50 m high
  - Max Height at about 20 sec



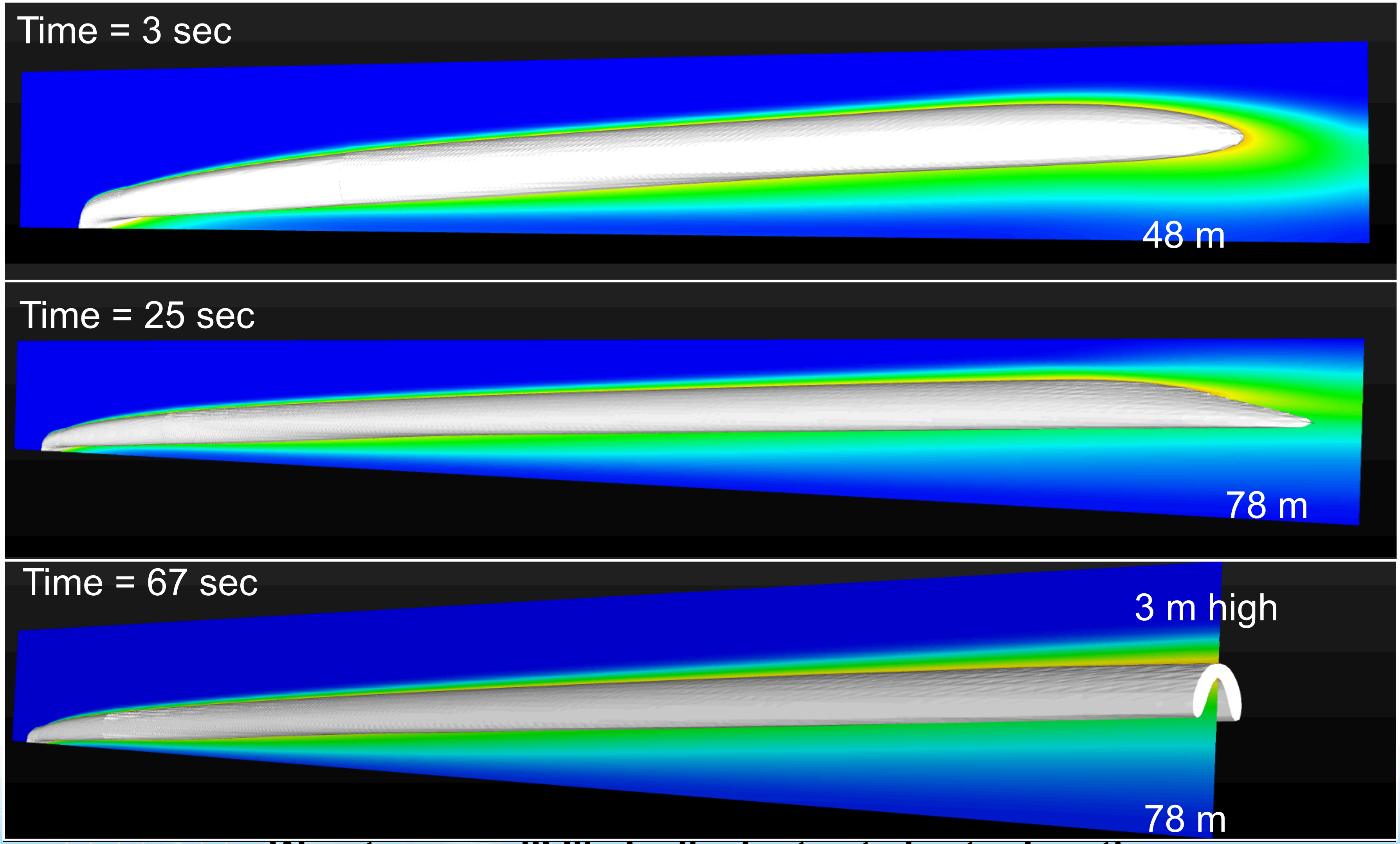
CFD of SF-BREEZE LH_2 Release With 5 knot Wind

- White shows flammable mass with volumetric concentration between 8%-75%



- Jet-in-Crossflow creates counter-rotating vortices
- Light weight H_2 pushed by wind
- Max: 20 m long, 8 m high @ 14 sec

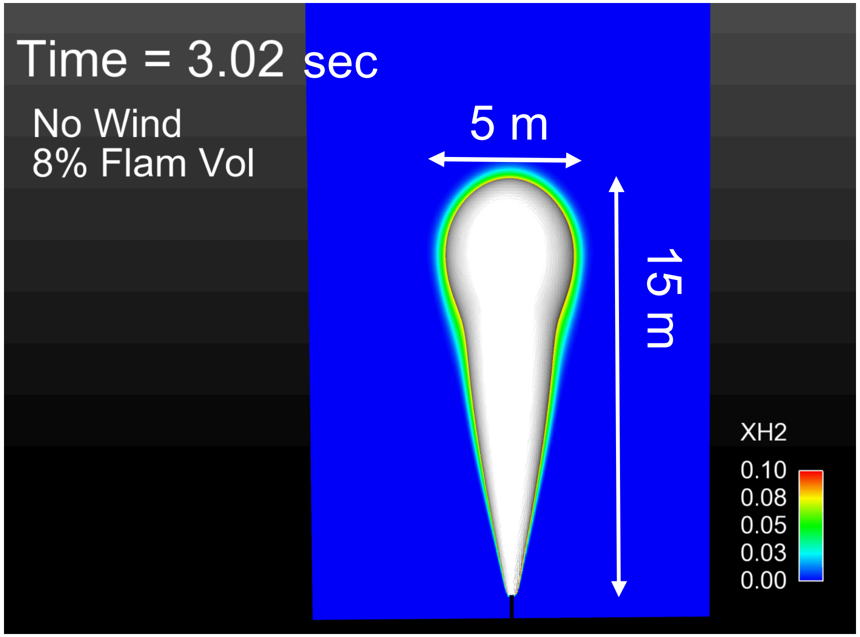
CFD of SF-BREEZE LH_2 Release With 30 knot Wind

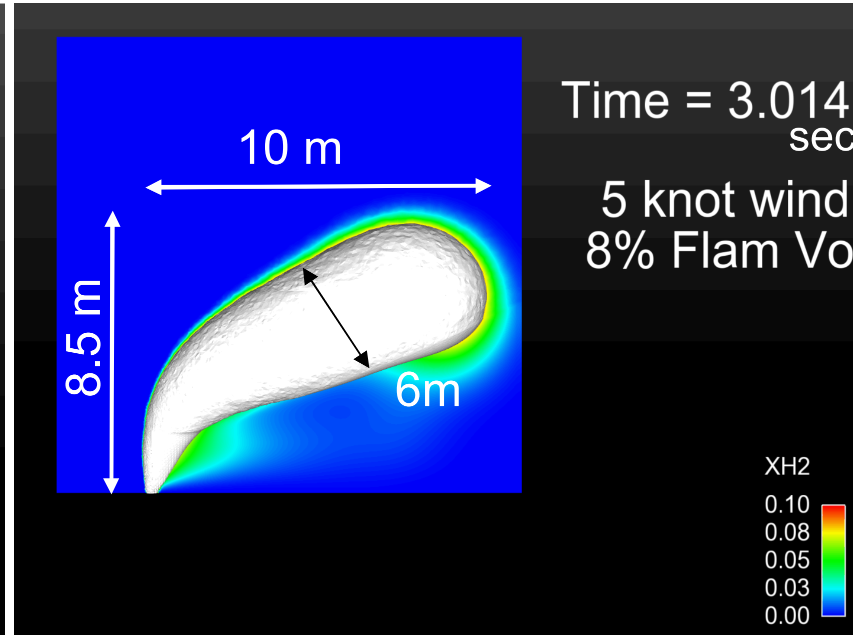


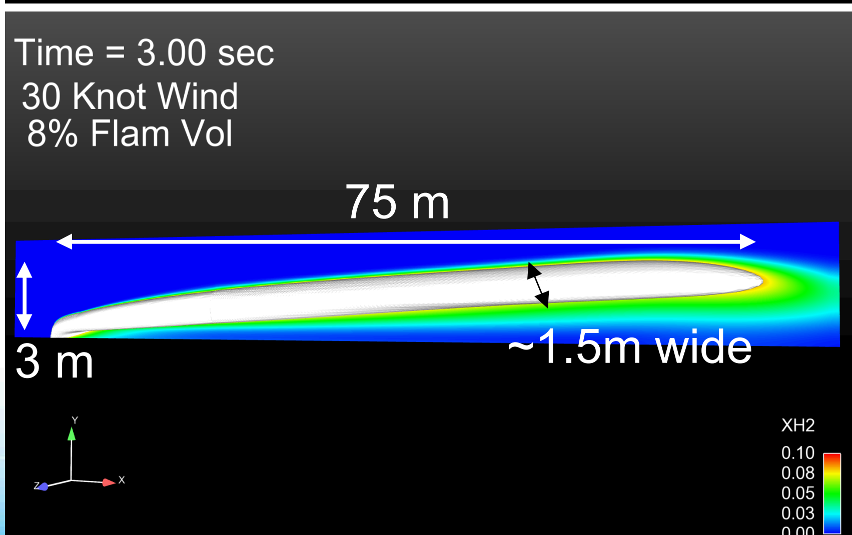
Worst case, will likely dissipate at shorter lengths

Does not include effect of downstream air disturbances/turbulence

Wind speed increases dissipation



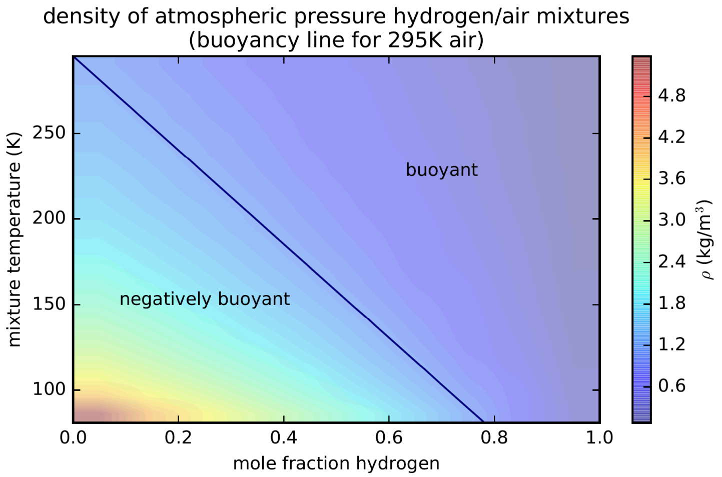


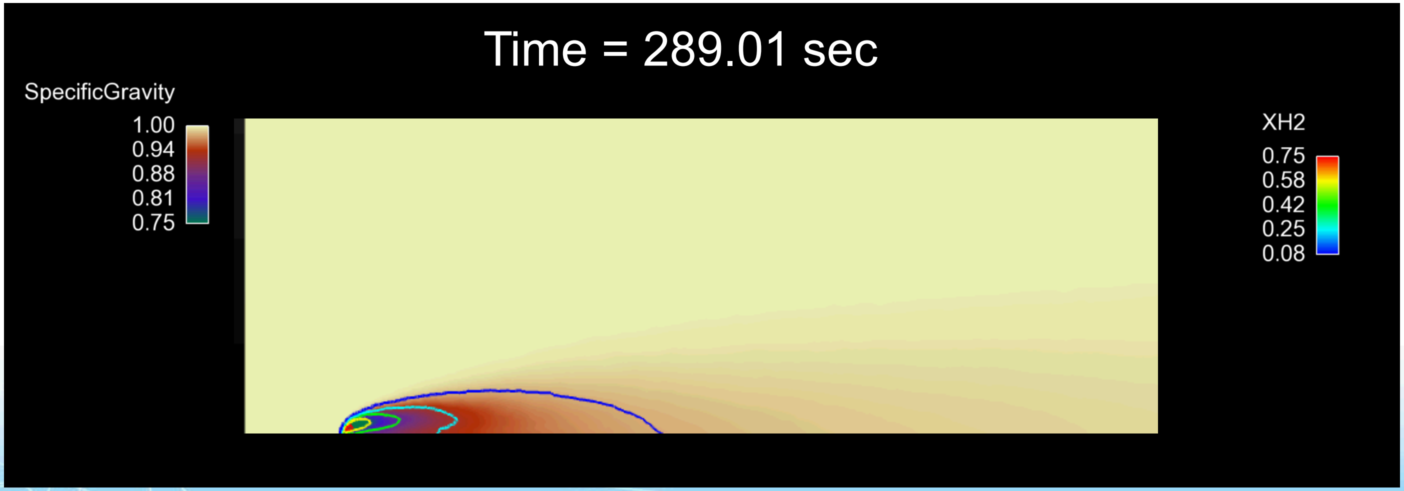


H_2 Mass	No Wind	5 Knots	30 Knots
Total	28.1 kg	28.0 kg	27.6 kg (out end)
Flammable	25.3 kg	23.8 kg	21.1 kg

Buoyancy

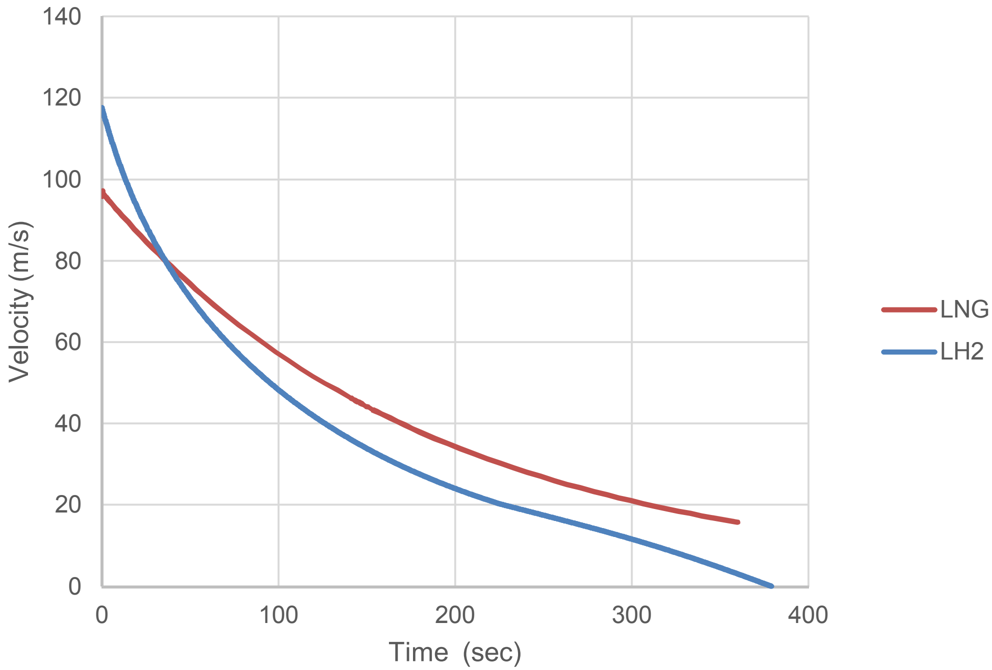
- Flammable concentrations will be positively buoyant
- Near the vent is coldest, but has highest H2 concentration
- Specific Gravity $= \rho / \rho_{air}$
  - $\rho_{air} = 0.001196\ kg/m^3$
- SG < 1 is positively buoyant





Comparison to LNG

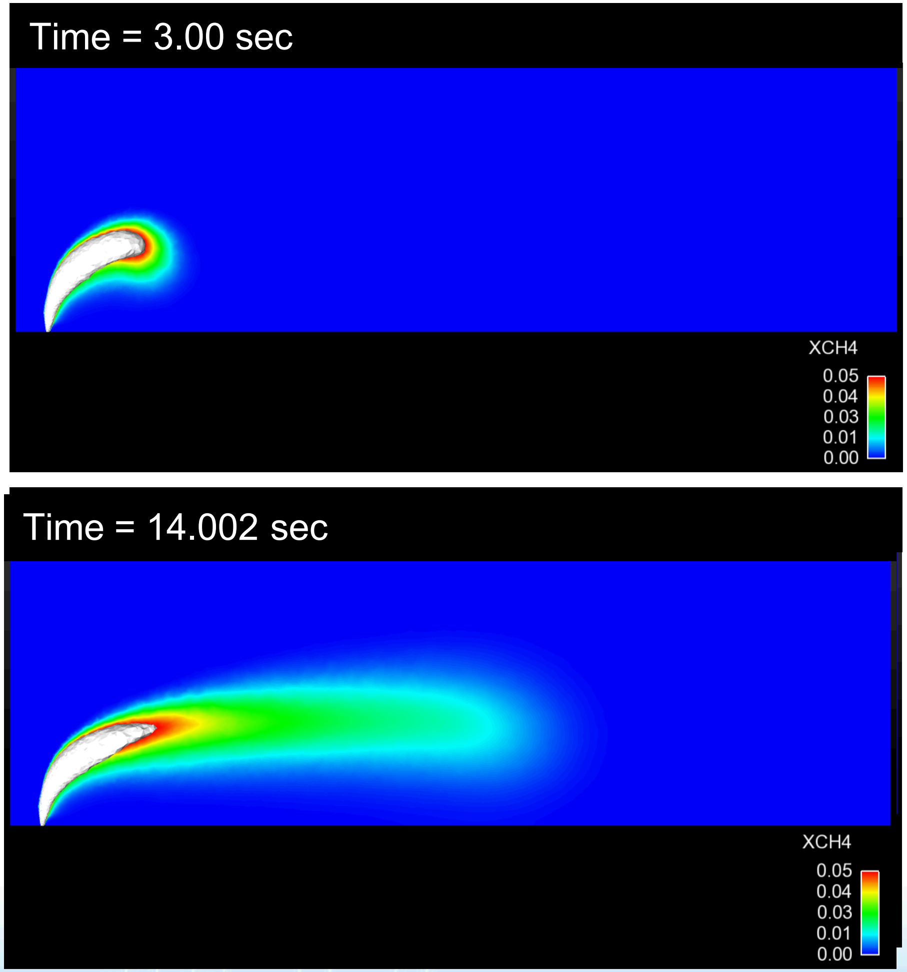
- Same:
  - Leak size – 1”
  - Tank pressure – 150 psi
  - Tank volume – 4500 gal
- Different:
  - Mass flow rate
  - Momentum
  - Time to empty



Comparison to LNG – 5 knot wind

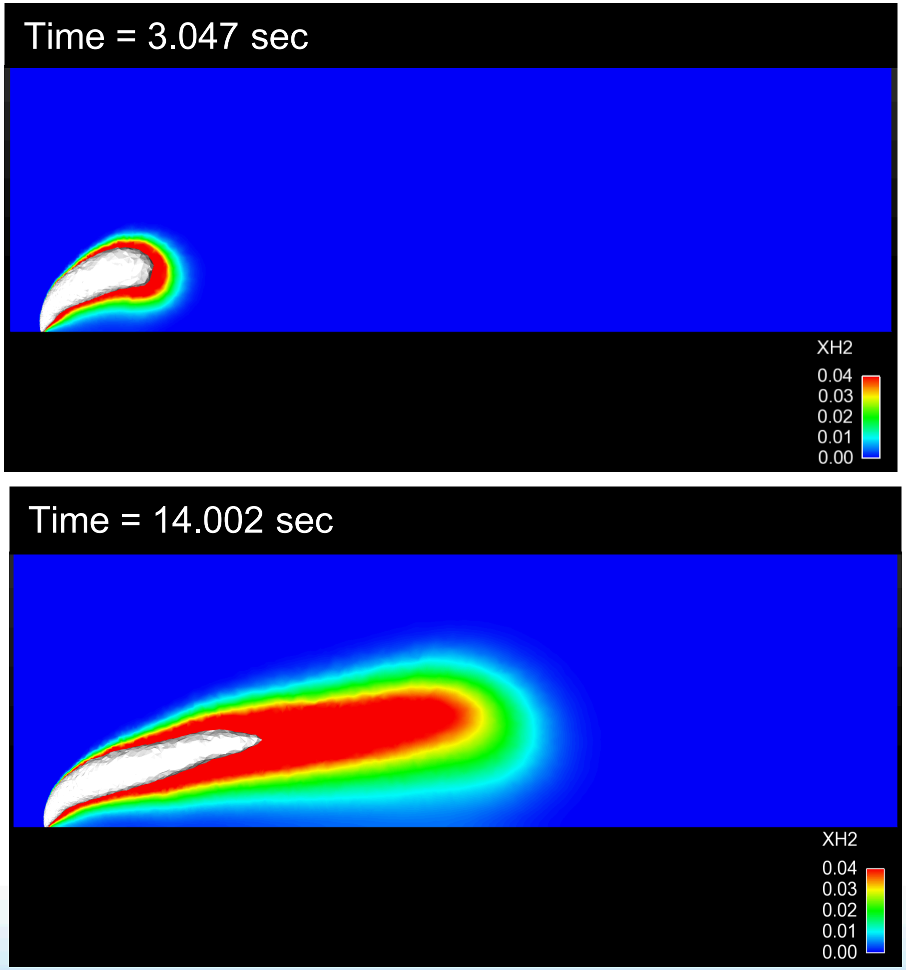
- Equivalent leak size, tank pressure, and tank volume

LNG Release



Max Flammable Plume:
10 m long, 9.5 m high

H2 Release



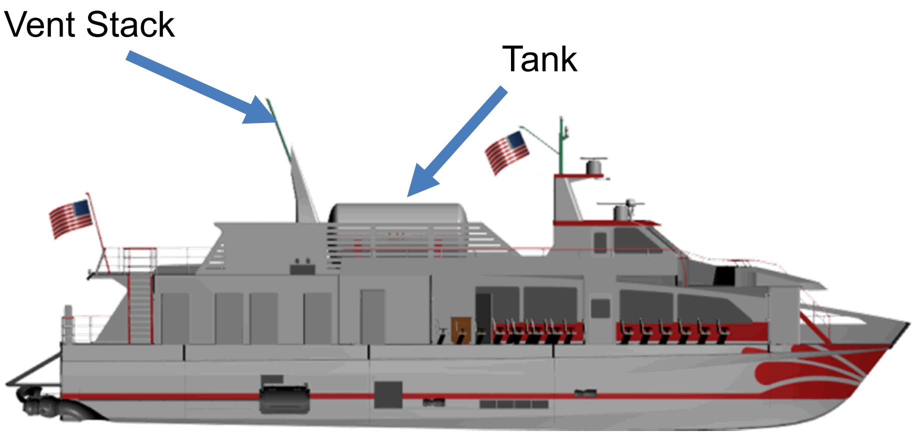
Max Flammable Plume:
20 m long, 7.7 m high

Outline

- SF-BREEZE Feasibility Study
- **Gas Dispersion Analysis**
  1. Abnormal Blowdown
  2. **Normal Boiloff**
  3. Fuel cell room

Scenario 2: Normal Venting due to Boiloff

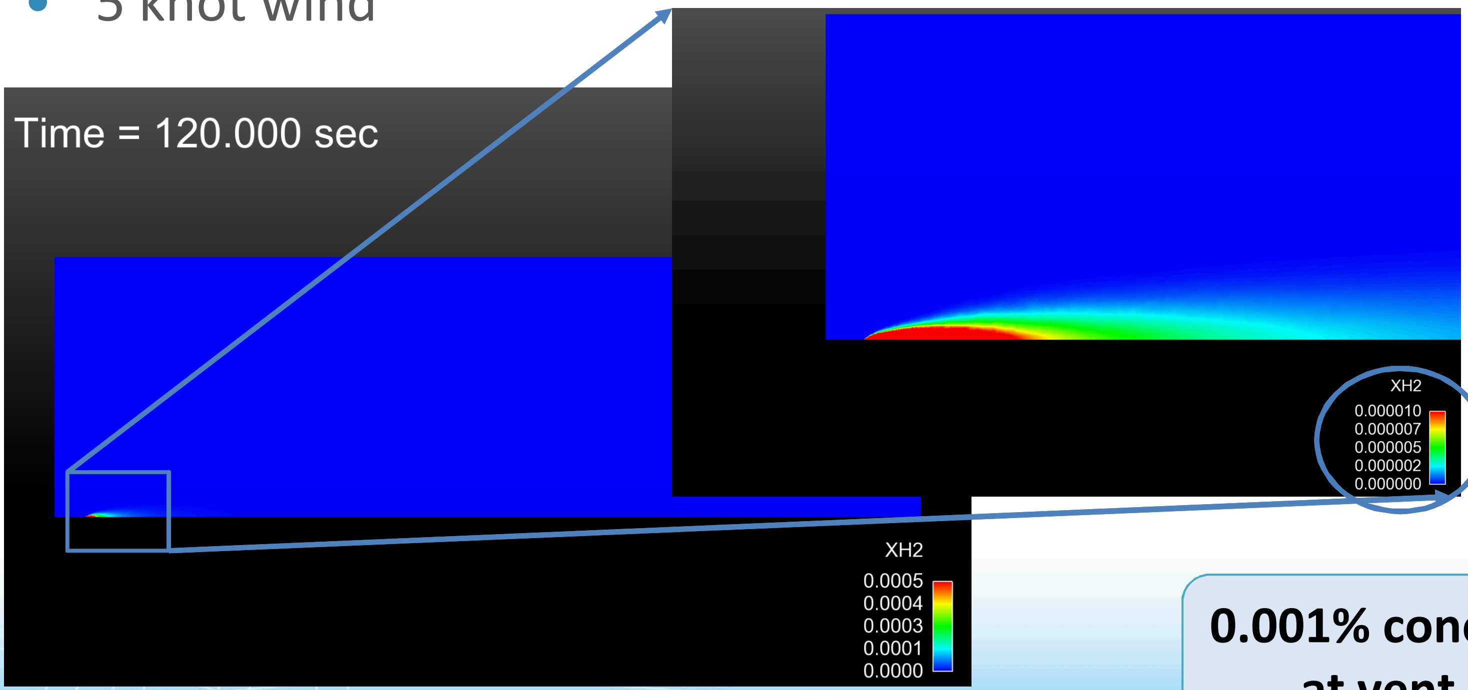
- Pressure will build up if LH_2 tank is not used for several days
  - Tank Dimensions
    - 150 PSI
    - ~4500 gallons
  - Vent Stack
    - ~7 inch internal diameter
    - 25 feet tall (7.5 m)



  - 1% of tank per day assumed (0.6% is expected)
    - 1200kg tank -> 12 kg/day boil off
  - Currently intentional releases of H_2 are not allowed while docked
    - Turn on fuel cells or some other way of reducing pressure needed

Scenario 2: Boil-off
Boil-off produces no flammable mass

- Steady state in tank – release limited by liquid hydrogen boiling to vapor and escaping
- 1% of tank per day assumed (0.6% is expected)
- 1200kg tank -> 12 kg/day boil off through a 2" valve
- 5 knot wind



0.001% concentration at vent outlet

Outline

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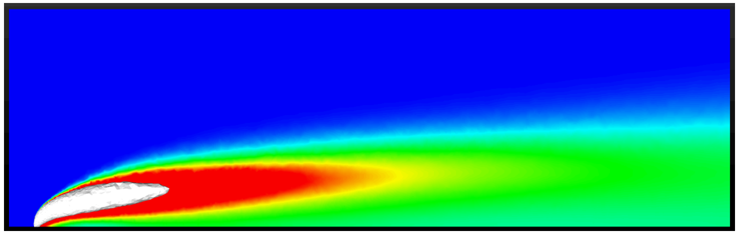
San Francisco Bay Renewable Energy Electric vessel with Zero Emissions (SF-BREEZE)

Examination of Maritime Hazardous Zone Regulations Applied to Hydrogen



Scenario 3: Leak inside a fuel cell room

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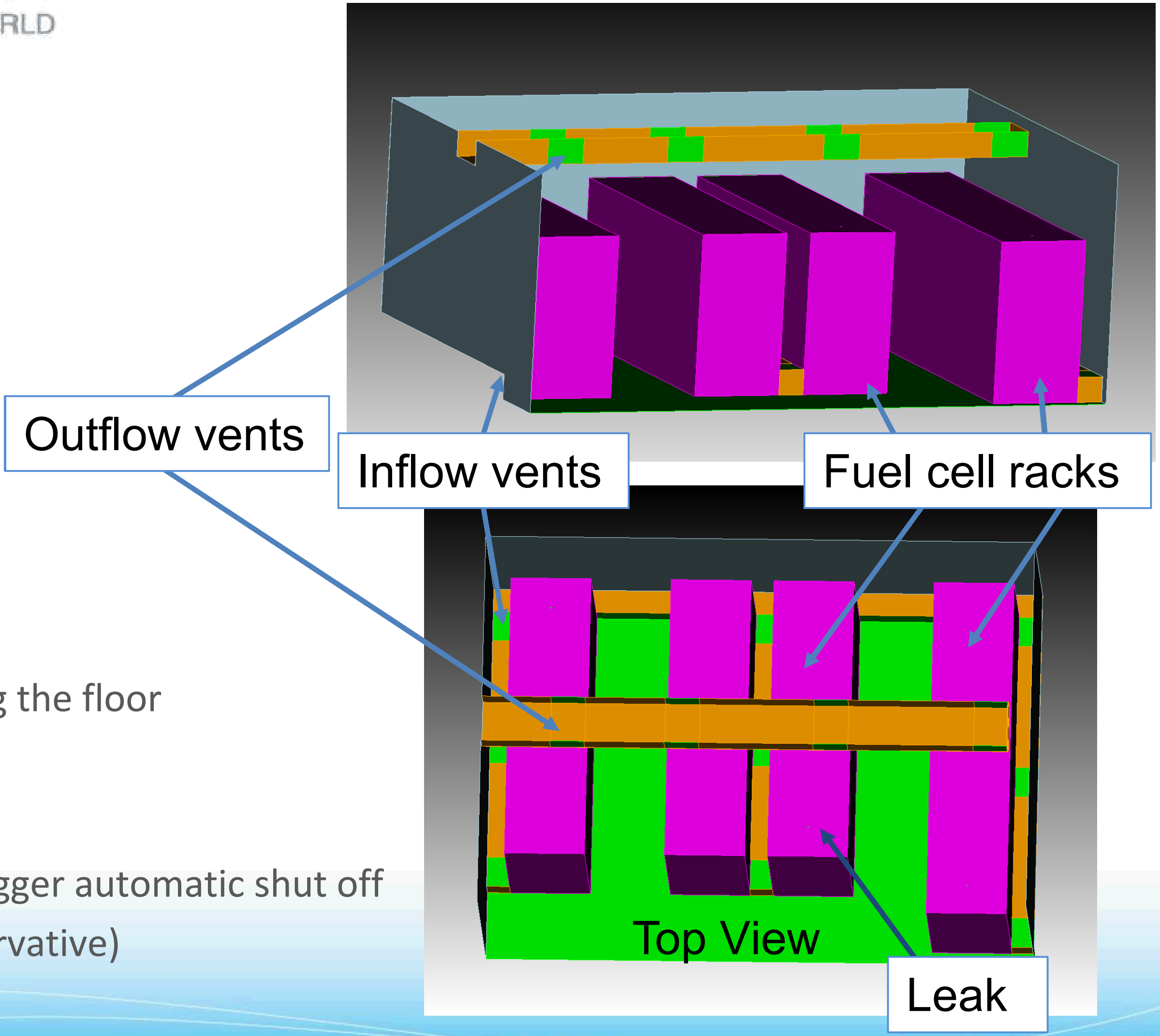
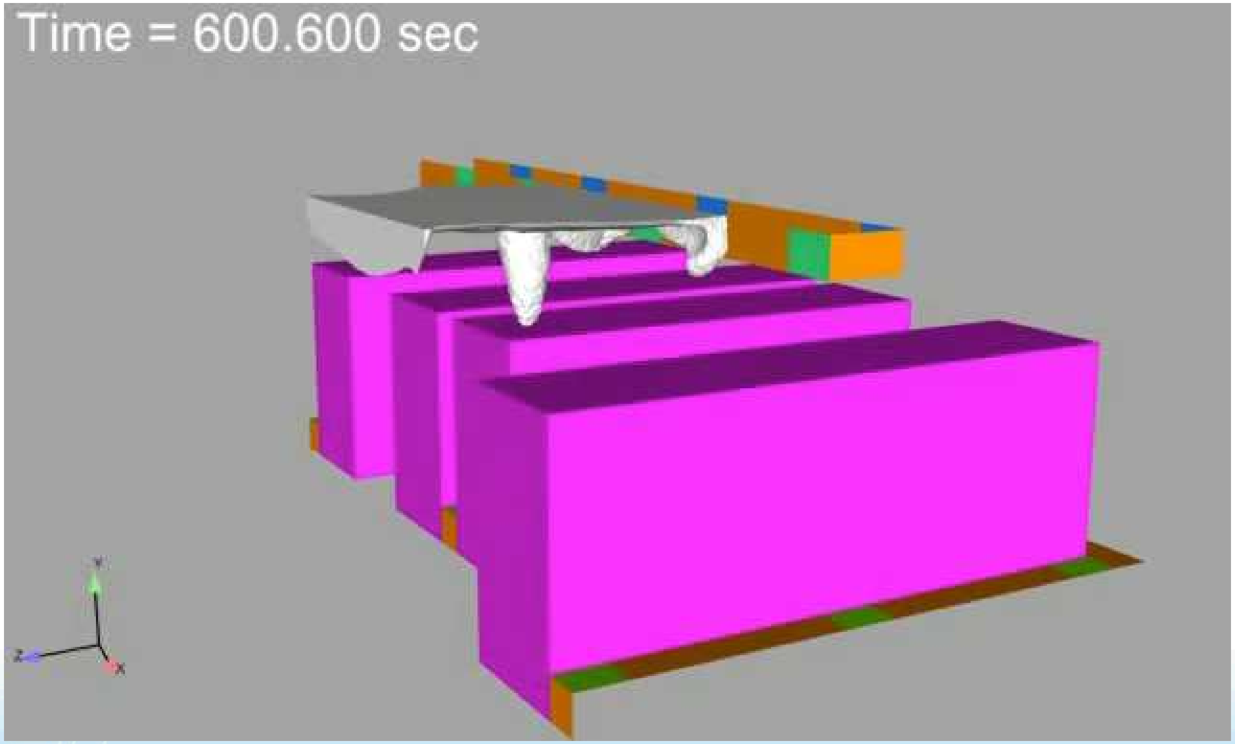


- Ventilation:
  - 200 cfm from 9 vents along the floor
  - Outflow vents near ceiling
- Leak from top of one rack
  - Pressure sensors would trigger automatic shut off
  - Stopped after 2 sec (conservative)

Fuel Cell Room

- Leak
  - Pressure = 100psi, 1” leak diameter
  - Starts at 600 sec (10 min to set up ventilation)
  - Stopped after 2 sec



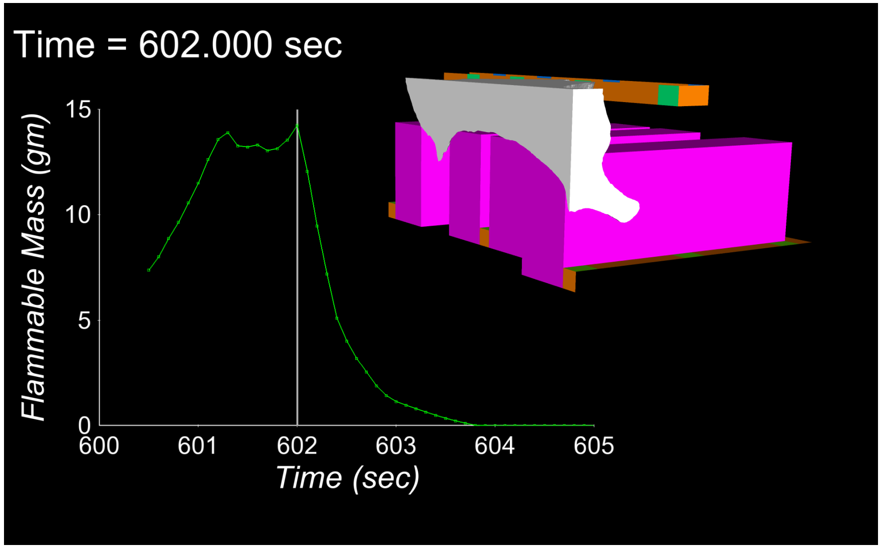
Flammable volume of H_2 can be used to determine potential overpressure hazard

Flammable mass : Cumulative fuel mass mixed into flammable concentrations (mixtures between 8% and 75% by volume for H_2-air)

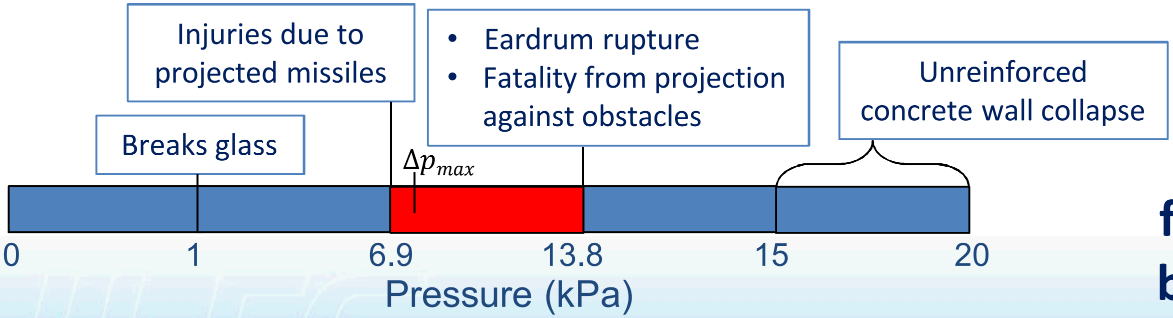
$$\Delta p = p_0 \left\{ \left[\frac{V_T + V_H}{V_T} \frac{V_T + V_{stoich}(\sigma - 1)}{V_T} \right]^{\gamma} - 1 \right\}$$

C. R. Bauwens, S. Dorofeev, Proc. ICHS, 2013.

p_0:	Ambient pressure
V_T:	Facility volume
V_H:	Expanded volume of pure H_2
V_{stoich}:	Stoichiometric consumed H_2 volume
σ:	Stoichiometric H_2 expansion ratio
γ:	Air specific heat ratio (1.4)



Potential Consequences:



$$\boxed{\Rightarrow \Delta p_{max} = 7.7 kPa}$$

Chance of small injuries from overpressure — Local blast waves not considered

American Institute of Chemical Engineers, 1998.

Summary of Results

Scenario 1: Abnormal Blowdown

- Hydrogen plume shape is greatly influenced by the wind due to large density difference compared to air
- Plume is always positively buoyant even when very cold H_2 (70 K)
- Plume of flammable H_2 will be longer than plume of flammable natural gas

Scenario 2: Normal Boil-off

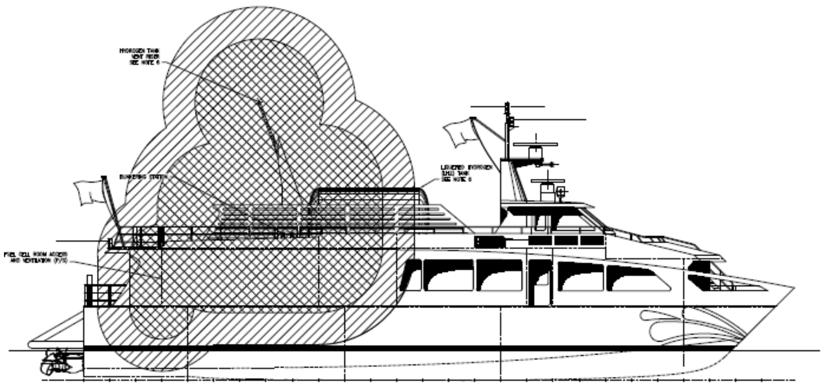
- During "boil off" venting there is no flammable concentration of gas

Scenario 3: Fuel cell room leak

- Large leak in fuel cell room will have flammable concentrations for only a very short period of time after source is shut off
- If ignited, will produce moderate overpressures

Next Steps

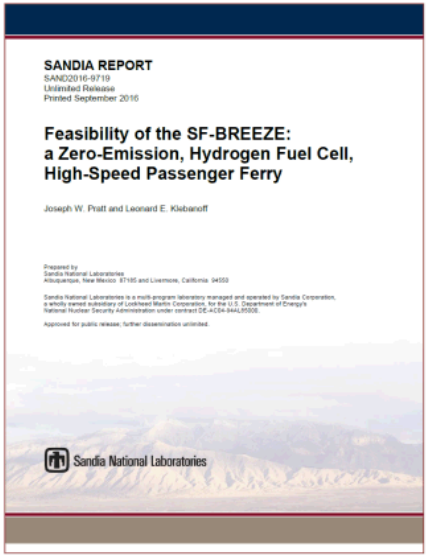
- Consultation with stakeholders, in particular USCG, ABS, and DNV-GL:
  - Refine results
  - Determine how to apply to hazardous zones in the code
  - Define follow-on studies



Thank You!

For more information visit:

maritime.sandia.gov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Feasibility of the SF-BREEZE:
a Zero-Emission, Hydrogen Fuel Cell,
High-Speed Passenger Ferry

Joseph W. Pratt and Leonard E. Klebanoff

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BACK-UP SLIDES

SF-BREEZE by the numbers

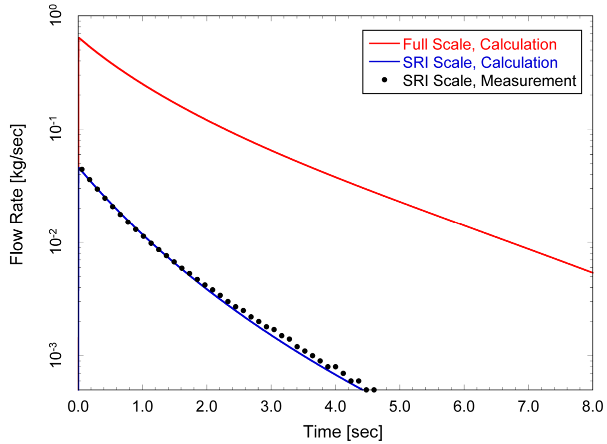
- Length 109’ x Beam 33’ x Depth 11.25’
- Full Load Draft ~ 4.6’
- Full Load Displacement ~133 LT
- Passengers: 150
- Service Speed: 35 knots
- Tonnage: 79.86 GRT
- Passenger Cabin Forward, Fuel Cells Aft
- LH_2 tank located on centerline (>B/5 from side)
- Propulsion power 4.4 MW, installed power 4.92 MW

- Optimization on this design is currently underway

Propulsion system architecture

1. Fuel cells feed DC-DC power converter to regulate voltage
   - 41 Fuel cell units – 120 kW x 41 = 4.92 MW
     - 4.6 MW for propulsion, 120 kW for other loads, remainder is margin
2. DC-DC power converters feed DC-AC power inverters
3. DC-AC power inverters feed AC PM propulsion motors (2 x 2 MW Permanent Magnet AC motors)
4. AC PM propulsion motors feed linear jet or water jet propellers (2 x 2.6 MW)

Simulation Validations

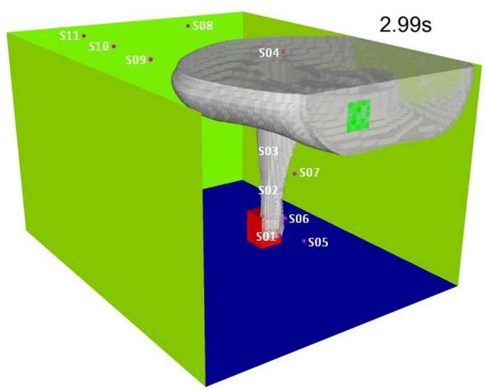


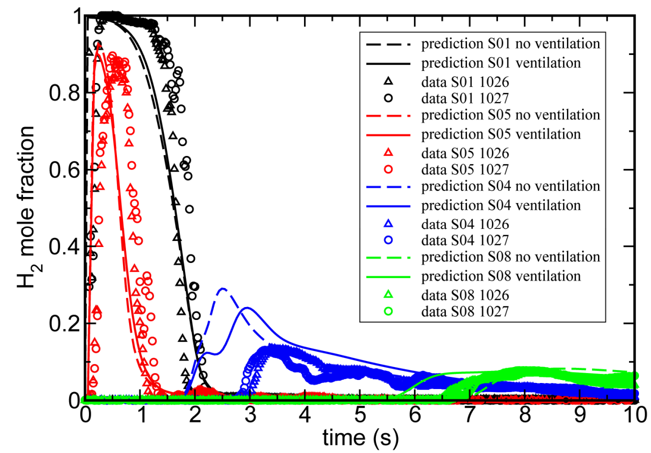
Blowdown release rates calculated via Sandia network flow solver (NETFLOW)

Winters, SAND Report 2009-6838.

Sandia "FUEGO" CFD flow solver

- Finite volume
- Compressible Navier-Stokes
- k-ε turbulence model
- Slip isothermal walls (294 K)
- ~10 cm mesh spacing



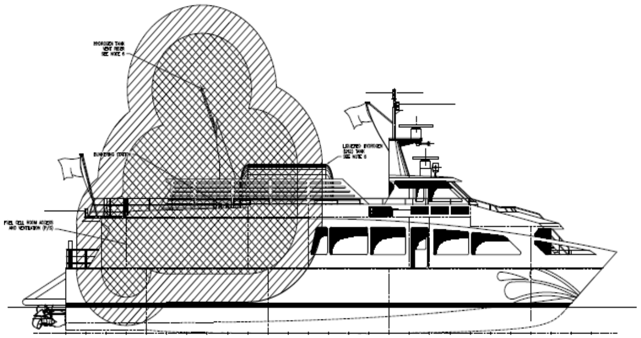


Houf et al., Int J H2Energy, 2013.

Methodology previously validated against large-scale hydrogen blowdown release experiments

Purpose

- Goal
  - Inform accurate hazardous zone requirements for hydrogen
- Benefit
  - Avoid situations that are unsafe
  - Avoid placing undue burden on vessel design and layout
  - Enable faster and easier approval



Method

A. CFD (gas dispersion) on most typical release scenarios with hydrogen and natural gas (to see the differences)
   1. Work with experts at USCG and Class to define most representative vent/release scenarios
   2. Configure and run models
   3. Analyze results
   4. Present results to MARAD, USCG, and Class and revise/refine/repeat as needed

B. Harmonization of NFPA and IGF prescriptive hazardous zones

C. Using results of (A) and (B) propose revisions to IGF codes as needed

LH_2 and LNG are similar cryogenic fuels

LH_2:

Liquid Normal Boiling Point = 20 K (-253 C).
Liquid Density = 71 g/L
Lower Heating Value = 120 MJ/kg

LNG (LCH_4):

Liquid Normal Boiling Point = 111 K (-162 C).
Liquid Density = 422 g/L
Lower Heating Value = 45 MJ/kg

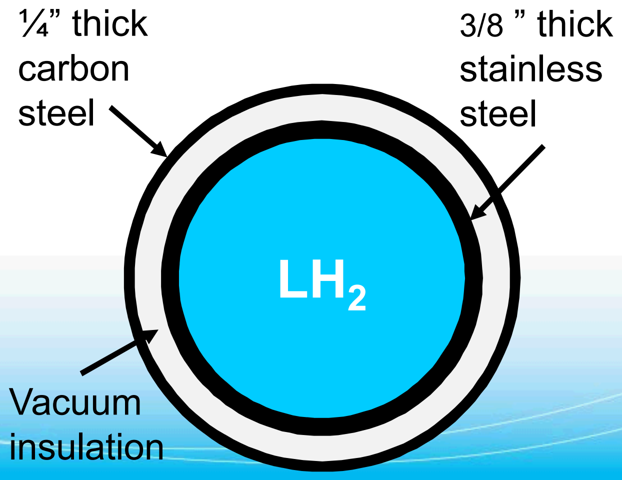
For the same amount of stored energy:

- **LH_2 is lighter** (m = 0.38 x LNG)
- **LH_2 is bigger** (V = 2.4 x LNG)

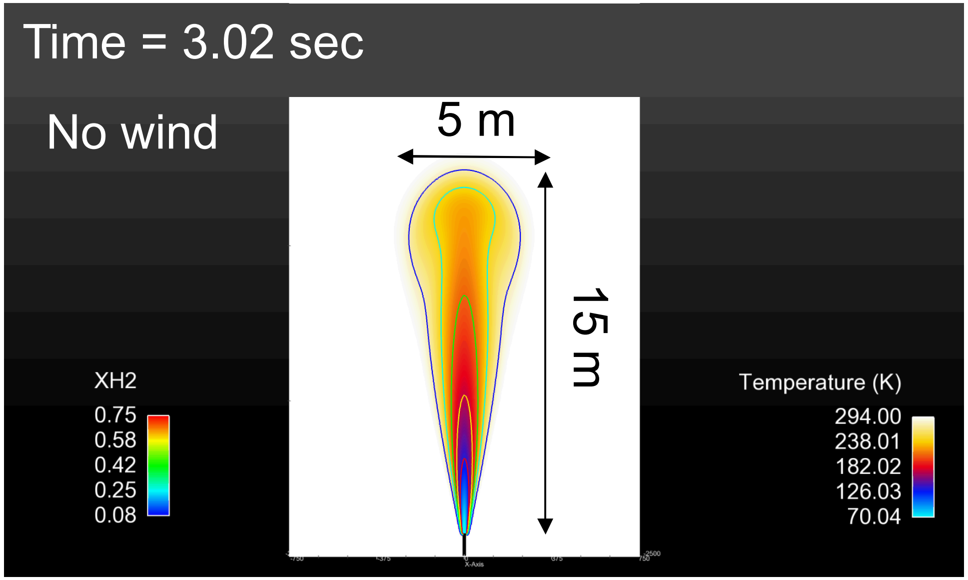
LNG and LH_2 are stored in similar ways:

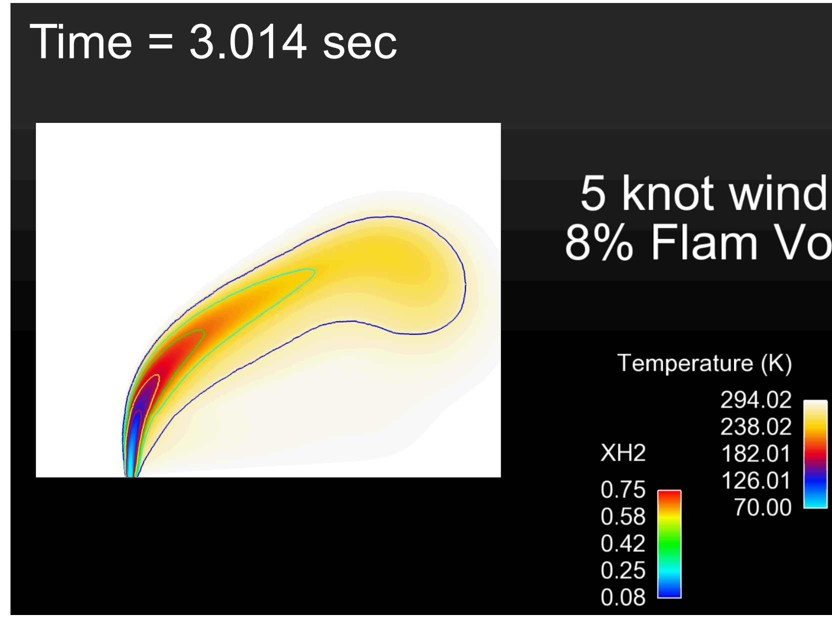
LH_2 Storage Tank on Trailer

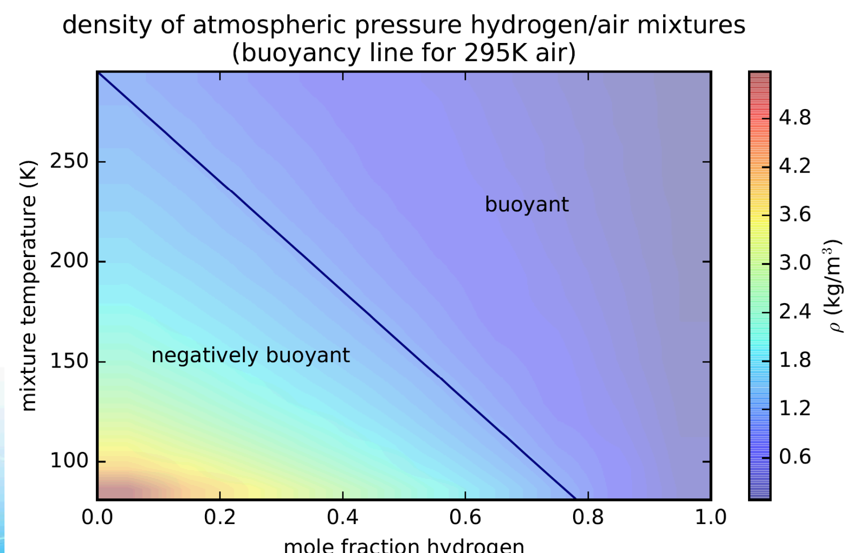
LNG Storage Tank on Trailer

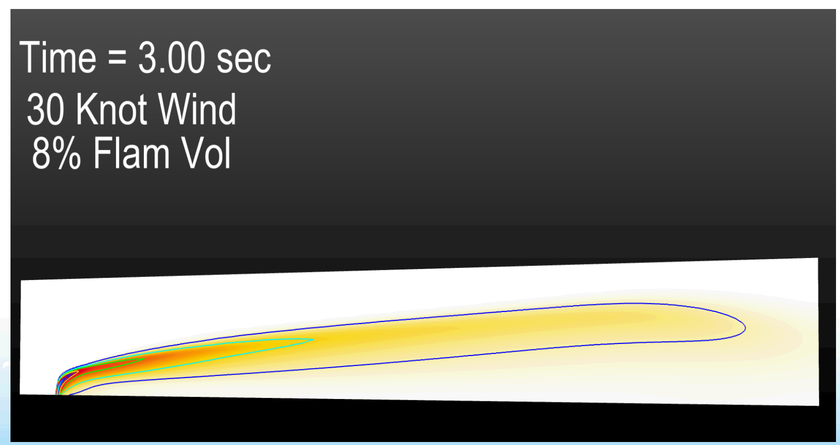


Temperature: Cold at high concentrations









70 K = -203 ºC = -333 ºF

Hazardous Zones Philosophy

- Based on guidance for LNG in IGF code
  - USCG recommendation
  - Comparison of LH_2 and LNG Properties With a Focus on Safety – Sandia
- Emergency Shut Down (ESD) arrangement
  - Two independent fuel cell rooms provide redundancy
- LH_2 tank and fuel delivery components located on open deck
- Bunkering station located on open deck